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COORDINATED FUSE-CONTROLLER SYSTEM FOR MULTIPLE ARCJET OPERATION

See-Pok Wong

December 1991

Final Report

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PHILLIPS LABORATORY
Propulsion Directorate
AIR FORCE SYSTEMS COMMAND
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FOREWORD

This final report was submitted on completion of this phase of JON: 1IT100BL by the OLAC PL/RKAS Branch, at the Phillips Laboratory (AFSC), Edwards AFB CA 93523-5000. OLAC PL Project Manager was Salvador Castillo, Capt, USAF.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

Salvador Castillo

SALVADOR CASTILLO, CAPT, USAF
Project Manager

BERNARD BORNHORST
Chief, Space Propulsion Branch

FOR THE COMMANDER

PETER VAN SPLINTER
Director,
Applications Engineering Division

RANNEY G. ADAMS
Public Affairs Director

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An innovative approach of connecting multiple arcjet thrusters to a single arcjet power conditioning unit (PCU) is presented. The approach uses fuses and a coordinated electronic controller to perform the functions of operating multiple thrusters with one PCU, therefore eliminating the need for high current, high voltage arcjet selector switches. Phase I effort will design the controller and identify the proper fuse as well as conduct liaison with other high power arcjet experimenters to verify this innovative approach.

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EXECUTIVE SUMMARY

We have investigated an innovative technique to connect multiple arcjet thrusters to a single Power Conditioning Unit (PCU) in this SBIR Phase I program. This technique allows a single arcjet PCU to operate multiple arcjet thrusters without high power switches. This is important because arcjet thrusters have a very limited lifetime it usually requires more than one thruster to complete a meaningful mission such as orbit raising.

We carefully examined the key issues that could impact the feasibility of this approach in this program. The single most uncertain issue is the risk of unwanted breakdown in the idle thrusters. Based on a simple mathematical model, we estimated the gas pressure is an order of magnitude below the threshold level. The result of the program was encouraging. We recommend to resolve the uncertainties in Phase II experimentally. This report presents the analysis and information on those key issues along with our recommendations on further investigations.

Propellant switching is an attractive alternative compared to mechanical / solid state switches to transfer power between arcjets, which are a significant operational risk in themselves. The small chance that shorted thrusters or unwanted breakdown may interfere with propellant switching could have a lower risk than the reliability of other switching. Furthermore, these potential problems could be accommodated. This will be dealt with in Phase II.

BACKGROUND

The key application for a high power arcjet system is for orbit raising, with an Electrical Orbit Transfer Vehicle (EOTV). The typical lifetimes of such missions are 2-4 thousand hours. The life expectancy of one arcjet thruster is significantly shorter. The longest demonstrated operation of a single high power arcjet is 572 hours; and the estimated design goal is about 1500 hours. Therefore, multiple thruster operation is needed to achieve meaningful missions.

On the other hand, the life expectancy of the arcjet Power Conditioning Unit (PCU), is significantly longer than the arcjet itself, because all the components used in the arcjet PCU are solid-state devices. In fact, arcjet PCUs are expected to have a lifetime of typical EOTV missions. Therefore, if one wants to use an arcjet PCU effectively, one needs to connect more than a single thruster to a common PCU.

An obvious concern when multiple thrusters are connected to a single PCU is the need for a high current and high blocking voltage switch. A space qualified switch that meets this requirement is not presently available. Even when such a switch is developed, its resistive loss could add significant burden to the power sources (solar panels) and waste heat management (radiators).

The essence of the present research program is to investigate an alternative approach which eliminates such a switch. Before we go into the details of this chosen approach, let's first review all the alternatives.

Alternative 1: Using multiple thrusters with a single PCU that are connected through conventional electrical or mechanical switches. (Figure 1.a)

Alternative 2: Using multiple thrusters with individual dedicated PCUs. (Figure 1.b)

Alternative 3: Using multiple thrusters connecting to a common PCU without switches. (Figure 1.c)

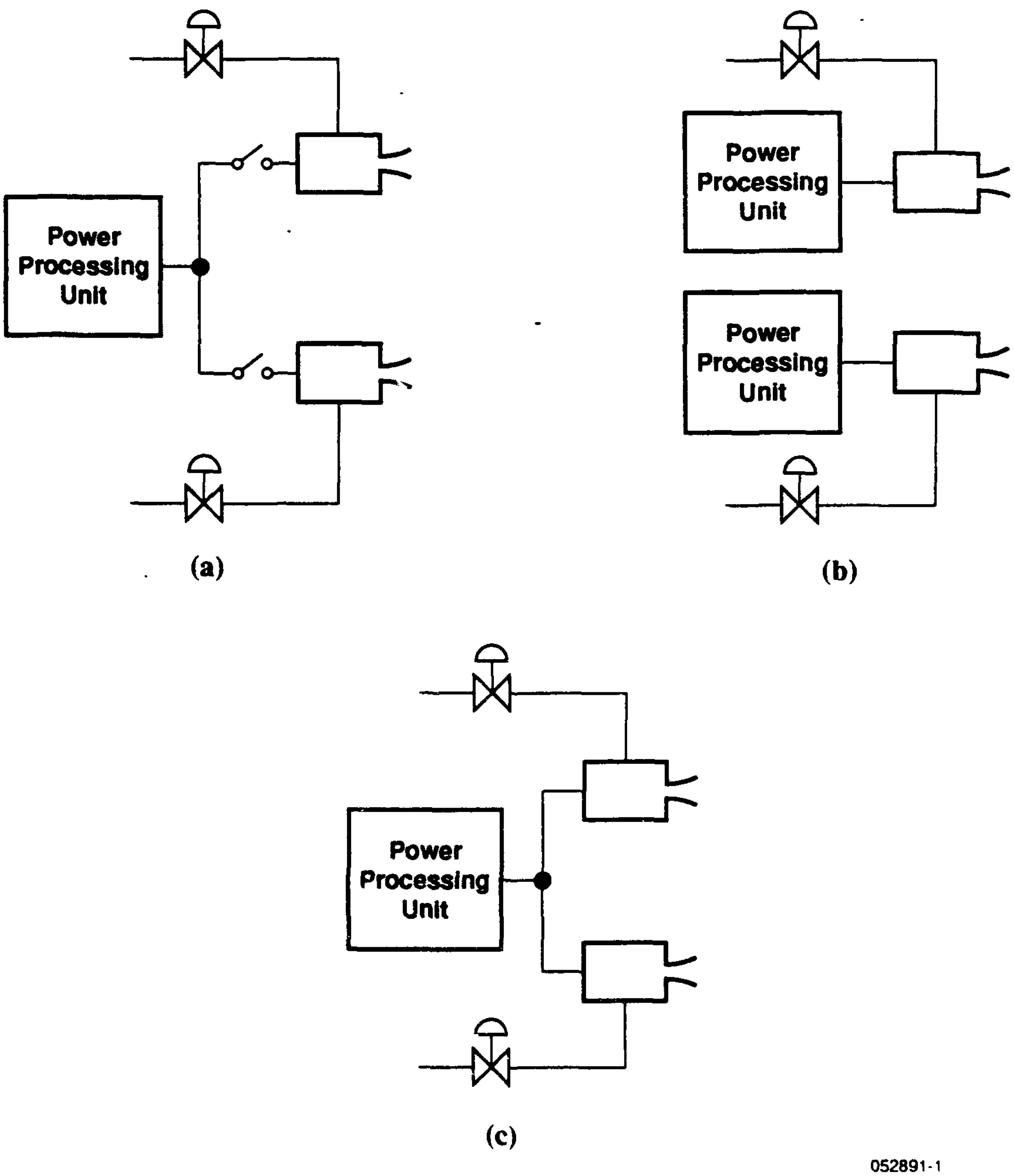


Figure 1
Configurations of Multiple Thruster Arcjet Systems

The disadvantage of Alternative 1, as described above, is the need for an electrical or a mechanical switch that can handle hundreds of amperes and block thousands of volts. Selecting this alternative may necessitate a major development program for this switch.

The disadvantage of Alternative 2 is the need for a large number of arcjet PCUs. As mentioned above, the life expectancy of a PCU is significantly longer than that of the thrusters, and it is likely to be longer than the whole mission. In a configuration with multiple PCU's, they will be under utilized and this results in redundant expensive hardware with mass penalties for the system.

Alternative 3 is very attractive and the question is: Does it work reliably. This approach overcomes the difficulties of the first two alternatives and offers the beauty of simplicity. The basic idea of this approach is to use the thruster itself as the switch and the propellant flow as the control for the electric current. All thrusters would be electrically connected in parallel in such a configuration. The same voltages will be applied across the electrodes of all thrusters. However, only the selected thruster, provided with propellant flow, could be ignited and become conducting. The rest of the thrusters would remain nonconducting.

Because of the cost and mass saving associated with this approach, we believe this is the preferred choice, if it can be made to work reliably. Therefore, the technical objective of this program is to investigate and find ways to guarantee, at least gain confidence, that the arcjet system using Alternative 3 will properly perform the thruster selection function.

PHASE I PROGRAM

Survey of Opinions from the Arcjet Community

Since using propellant to select the thrusters is a new concept, we would like to explore this concept with our colleagues in the arcjet community and hear their opinions. Therefore, the first task of this program was to generate and send out a survey question package, then analyze the responses. The objectives of this survey were:

1. Introduce this idea to the community.
2. Initiate discussions about this subject.
3. Hear the pros and cons about this approach.
4. Catch the issues that we overlooked.
5. Promote the use of this approach if its feasibility is proven.

The following is the survey questionnaire

The first part of this document is a description of an innovative approach which eliminates the need for an arcjet selector switch in a single PCU, multiple thrusters arcjet system. The second part is a series of survey questions.

Your answers will provide guidance to the development of this approach.

1

How does this approach work?

- Does not use any switch.
- Connects all thrusters directly together.
- Uses propellant control to select the thruster.
- Uses a fuse to disconnect any unrecoverable and unopenable thrusters.

3

Why is this approach important ?

- It is difficult to find a selector switch that will meet the following requirements:
  - Conduct high current up to 300 A.
  - Block starting voltage up to 2000 V.
  - Be low enough in impedence that it will not pose additional thermal problems or reduce system efficiency.
- Even if a switch is available, it will add significant complication, weight, volume, and cost to the arcjet system.

2

Why does this approach work?

Facts:

- The arcjet thruster itself is an ignitable switch.
- It will not conduct current even with voltage across the electrodes, as long as it is not ignited.
- It is not ignitable if there is no propellant flow.

Conclusion:

An arcjet system can use the thrusters themselves as their own selector switchs.

4

Survey Questions

More Benefit

Automatic system recovery as intermitent short path removed.

```
      (programmable)        (determined by fuse)
Sense    60 sec.    high current  30sec.  fuse opened after
of short ---------> mode for      ------> 30 second, switch
circuit       |     fuse removal   |      to other thrusters
              |          |         |
              |          |         |
              |          |         |
              |          v         |
              | removable short-circuit |
              | path such as whiskers   |
              | growth opened by   |     system recover,
              v ohmic heating      v     back to normal
              ---------------------------> current immediately
```

5

Summary

- No high current, high voltage arcjet selector switch.
- All arcjet thrusters are connected to the arcjet PCU only through a fuse for emergency disconnect.
- Start pulse suppressor may be used if determined to be necessary.

6

The Advantages

- Simplicity.
- Reliability.
- Low mass and compactness.
- Efficiency.
- Cost saving.

7

Questions to you

- The Approach
- The Thruster Failure Scenario
- The Dry Firing
- The Fuse

8

The Approach

- Do you think this approach will achieve the goal? Why or why not?
- Do you see any concerns that have been overlooked? Which?
- Do you have another alternative suggestion? How?
- Do you know any test results that are relevant to this approach?

9

The Thruster Failure Scenario

- What is the mostly likely failure mode?
  - Excessive cathode material loss
  - Short-circuit path created by whiskers
  - Dielectric breakdown inside its internal structure
  - Others, _______________(please describe)
- Is 60 seconds a reasonable waiting period before the changing to high current mode for permanent fuse removal?

10

Survey Questions (continued)

The Dry Firing

(Applying a high voltage pulse to the thruster without propellant flow)

- Will it cause cathode (or anode) damage?
- What is the minimum pressure to guarantee no breakdown?
- Will it cause long-term degradation of the thruster?

11

The Disconnecting Devices

There are two types of disconnecting devices

- The regular fuse — opens passively after passing excessive current for a pre-determined period of time
- The externally activated disconnecting device (EADD) — opens actively after a signal is sent to the device

The trade-off issue:

The EADD is very expensive but may be needed if a thruster failed to start and conduct current but has a breakdown voltage lower than the start voltage so that it will prevent the high voltage pulse from starting-up other healthy thrusters.

12

The Question:

- Is the above mentioned scenario likely to happen?
- Do we need the EADD?

13

Thank you very much for your input. If you are interested in knowing more about this approach, we will be happy to send you a more detailed description. This package is designed to minimize your time to provide us your important input.

14

Survey Questions (continued)

We sent out the above package to 18 people and 14 of them sent back their responses. Thanks to the support of the respondents, we received a lot of useful information. The most frequently mentioned concern was the possibility of unwanted gaseous breakdown in the idle thrusters due to effluent propellant or material outgassing. The following section will be dedicated to this issue. Other issues mentioned in the responses included:

1. No space qualified fuses.
2. Radiated EMI due to additional cable length.
3. The duration of 60 seconds in the high current mode may be too long.
4. Current flow between the cathode of one thruster and the anode(s) of other thrusters.

5. Excessive energy stored in the cable capacitance during the high voltage start-up pulse, due to the additional cable length for more than one thrusters.

6. One or more thrusters failed in such a way that it cannot pass high current to blow the fuse, but leaks enough current to prevent other good thruster(s) from firing.

We do not think items 4 and 5 are of major concern. The majority of the current, if not all, will be returned to the anode of the same thruster. Even if there is a very small amount of current flow from the cathode of a thruster to the anode of another thruster, there should not be any adverse effect because the anodes of all thrusters are electronically connected together anyway. The energy stored in the cable should not be significant enough to affect the arcjet operation. The total length of the cable in a multiple thruster system should still be shorter than the 50 to 60 feet of cable used in the vacuum facility for arcjet testing. During testing, no damaging effect has been observed due to long cable length. Items 1, 2 and 3 are design details that have no impact on the feasibility of the approach. Only the last issue, which was suggested in our survey questionnaire and echoed by respondents, has a significant impact on the system design. If this scenario is real, an externally activated disconnecting device (EADD) must be used to disconnect the crippled thrusters. This issue will be discussed in detail in later sections.

Unwanted Gaseous Breakdown Of The Idle Thrusters

When all thrusters are connected in parallel, both the steady state D.C. voltage and the high voltage start pulse will be applied to all thrusters. The only means to discriminate the idle thrusters is the absence of propellant. We believe the idle thrusters will remain nonconductive during the operation of proper thruster. However, concern has been raised about the high voltage start pulses. There is a potential danger of gaseous breakdown at the start pulse in or around the idle thrusters due to excessive outgassing of neighboring material, or the effluent propellant of the operating thruster.

In order to evaluate the probability of this unwanted breakdown, we examined to the Paschen Curve for low pressure gaseous breakdown. Before we discuss the implication of these curves, we should point out that the Paschen curves are generated by D.C. voltage rather than narrow pulses. Test performed in NASA LeRC indicated that the breakdown voltage of a pulse is higher than D.C. voltage.[1] However, we chose to ignore this fact in the following analysis so that the result derived from the Paschen curves will be a conservative estimate.

Figure 2 is a Paschen Curve for Hydrogen. The breakdown voltage is a function of the product of p (pressure) and d (distance between the electrodes). The distance between the cathode and the anode of the arcjet is on the order of 0.2 to 0.5 cm. However, the breakdown could happen between the cathode and the far part of the anode. To be on the safe side, we assume the value of d could be anywhere from 0.1 cm to 4.0 cm.

The minimum breakdown voltage occurs at $p \cdot d = >0.8$ cmtorr. Using the distance of 0.1 to 4 cm, the minimum breakdown occurs at 0.2 Torr or above. If the pressure around the idle thrusters

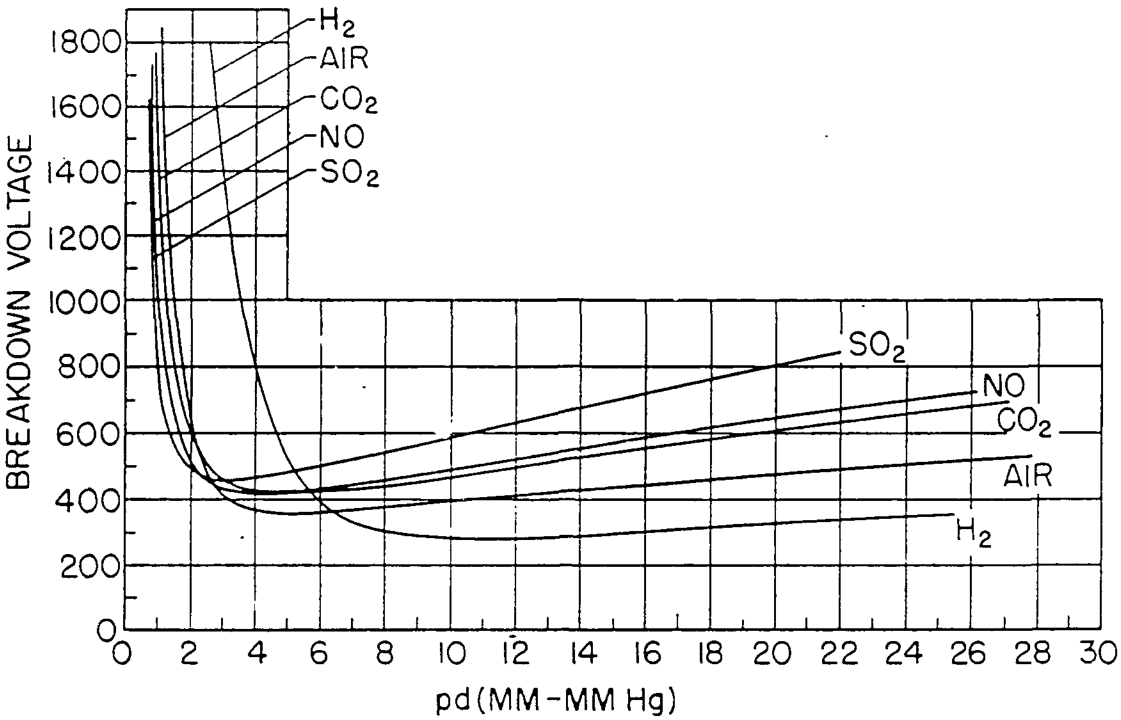


Figure 2
Paschen Curves for Various Gases

is about 200 mTorr or higher, breakdown can occur even with 250 V. Since the start pulse is about 2000 V, breakdown is imminent at this pressure.

200 mTorr allows breakdown at 2000V. What pressure is safe at 2000 V? Using the same curve but from a different point of view, we can see that the breakdown voltage exceeds 2000 V if p • d is less than 0.2 cm-torr. With the range of d being 0.1 to 4 cm, The breakdown pressure should be 50-2000 m Torr or higher. In other words, breakdown can be avoided if the pressure is kept way below 50 mTorr. The chance of breakdown diminishes as the pressure goes further below 50 mTorr.

We use hydrogen arcjet in the following example to estimate the gas pressure introduced by effluent propellant. An equation derived by Narasimha for a simple point source model can be used here to get a rough idea of gas pressure.[2] This equation is applicable for regions within the collisionless limit. The equation is:

$$n(r,t) = \dot{N} / (11.14 \cdot C_m \cdot r^2) \cdot \exp[-(r/C_m t)^2]$$

Where: t = time (sec)

r = distance from the point source (cm)

n = molecular density (no./cc)

$\dot{N}$ = propellant mass flow (g/s)

C_m = the most probable speed = $\sqrt{(2kT/m)}$

k = Boltzmann Constant (1.38×10^{16} erg/°k)

T = Temperature (degrees Kelvin)

m = mass (grams)

For equilibrium, i.e. $t = \infty$,

$$n(r) = \dot{N} / (11.14 \bullet C_m \bullet r^2)$$

We use the following assumptions:

			Comments
Temperature (T)	=	300°K	Before arcjet is ignited
Distance from thruster (r)	=	10 cm	Estimate
Propellant	=	Hydrogen	Molecules
Propellant flow rate ($\dot{N}$)	=	0.1 g/sec	typical flow for H_2 arcjet

And the following constants:

Boltzmann Constant (k)	=	1.38×10^{-16} erg/ °K
Avogadro number	=	6.02×10^{23} amu/gram
Acceleration of gravity (g)	=	981 cm/sec^2
Hydrogen Mass (m)	=	1.673×10^{-24} gram
Modal volume at STP (V_o)	=	2240C c.c.

Using the equation of $C_m = \sqrt{(2kT/m)}$, we have $C_m = 1.57 \times 10^5$ cm/sec.

Because hydrogen has 6.02×10^{23} atom per gram or 3.01×10^{23} molecule per gram, 0.1g/sec is equivalent to 3.01×10^{22} molecule/sec. Put the distance, the propellant flow and the most probable speed in the original equation, we have:

$$n\,(r{=}10\text{cm}) = 3.01 \times 10^{22} / (11.14 \times 1.57 \times 10^5 \times 10^2)/\text{c.c.}$$

$$= 1.72 \times 10^{14}\ /\text{c.c.}$$

To convert this molecular density to the conventional pressure unit, we use the hydrogen molecular density at atmospheric pressure,

$$n\,(\text{hydrogen @ 1 atm}) = 6.02 \times 10^{23}/22400\ \text{c.c.} = 2.69 \times 10^{19}/\text{c.c.}$$

By comparison, we derive the pressure of interest to be:

$$P\,(r{=}10\text{cm}) = 6.39 \times 10^{-6}\ \text{atm or}\ 4.86 \times 10^{-3}\ \text{torr}\ (\sim 5\ \text{mTorr}).$$

This pressure (5 mTorr) is an order of magnitude below the 50 mTorr pressure that is the threshold for 2000 V breakdown. Therefore, breakdown should not happen. We realize that this is a very simple model. Some local trapping areas faced the source may experience higher pressure than the open space. However, at the same time, this model over estimates the pressure by ignoring the fact that the velocity of most of the propellant has a large axial component which is pointing away from the idle thrusters. This effect should offset most, if not all, of the negative factors.

Another piece of interesting information provided by this simple model is the time constant. It equals to

$$r / C_m = 10 \text{ cm} / 1.57 \times 10^5 \text{ cm/sec} = 6.37 \times 10^{-5} \text{ sec.}$$

This number tells us that, if we can synchronize the propellant flow switching and the high voltage start pulse to within approximately 60 μsec, there may be a potential benefit of reducing the effluent effect due to the transient effect. We do not feel this technique is necessary. However, it is useful to know the time scale necessary for a synchronized switching approach.

Even though we do not feel the effluent will cause breakdown in the idle thrusters, we did collect some good ideas to minimize the unwanted breakdown if it happens or has the tendency to happen. These ideas were suggested either by our respondents or by SPI personnel.

A. Use a plume shield to minimize the effluent of propellant in the vicinity of neighboring thrusters. An artist concept of plume shield technique is shown in Figure 3.

B. Use a cap on the new and idle thruster. This cap would be removed by the propellant flow of the first use.

C. Synchronize the switching of the propellant flow and the high voltage pulse so that there is not enough time for the propellant to get close to the other thrusters (as we discussed above, the time difference should be less than ~60 μsec).

D. Select the material of the thrusters carefully to minimize outgassing. (Outgassing outside the thruster will not cause any breakdown because even the worst outgassing is still orders of magnitude lower than the propellant flow and therefore the pressure is also orders of magnitude lower than what we estimate for propellant effluent.)

Externally Activated Disconnecting Devices

When the arcjet thruster approaches the end of its life, its voltage will drop below the normal operating range. The arcjet PCU (or controller) in a multiple thruster system should sense this abnormal voltage reduction, turn the arcjet off, and switch to another thruster. (A multiple thruster controller design that will serve this and other functions is being proposed in a later section.) Under this scenario, no fuse or any kind of disconnecting devices is necessary.

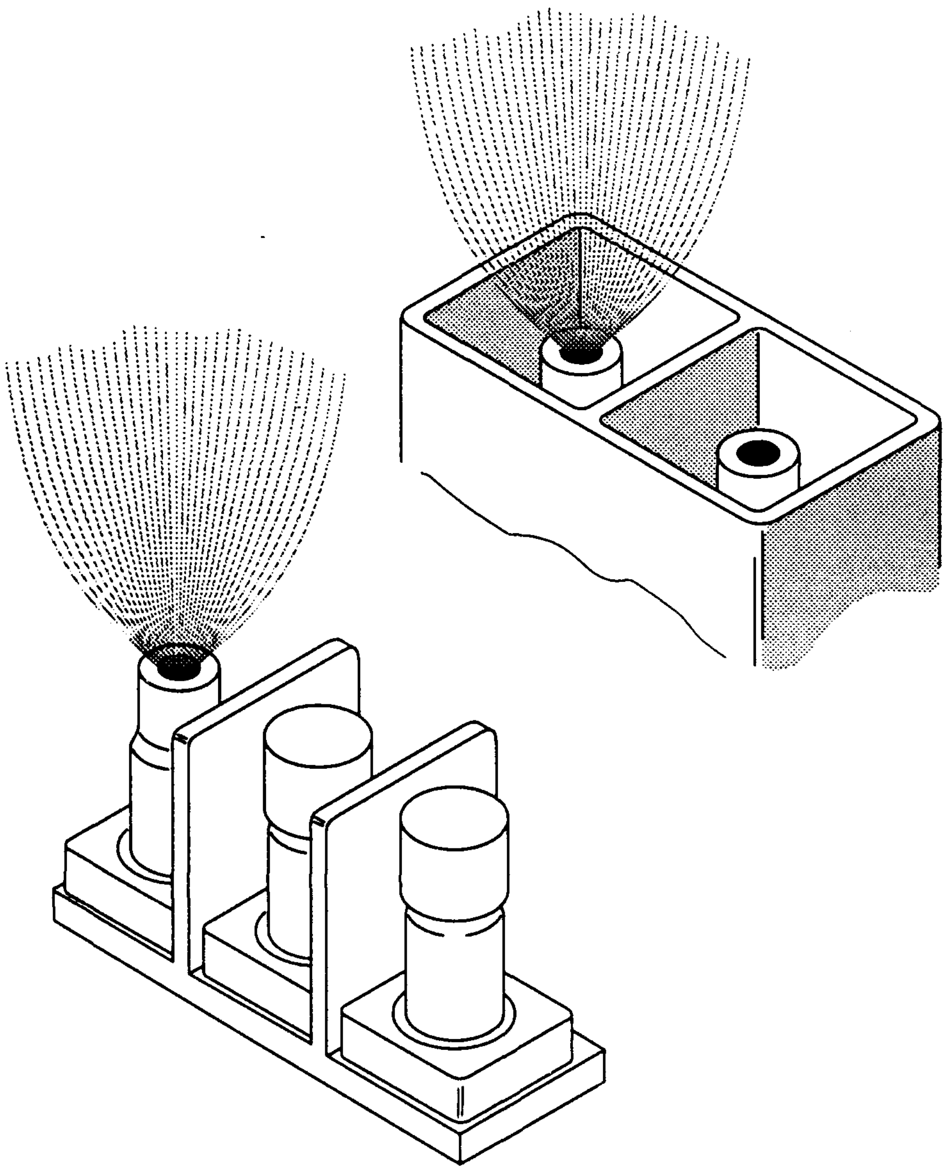


Figure 3
Artist Concepts of Arcjet Thruster Partition

How do we handle the situation when a thruster suddenly fails and becomes a shorted path? After this failure, the PCU will be held down by the short path and will not be able to operate any other thrusters. Of course, we should also ask whether this could happen or how unlikely this will happen. We will discuss this issue in a later section. In this section, let's first look into how to handle this scenario if it happens.

As suggested in our proposal, there are two kinds of disconnecting devices that can isolate a failed thruster which affects the normal operation of other healthy thrusters. The first one is the conventional fuse. The second one is the Externally Activated Disconnecting Device (EADD). (For clarification: we called it Chemically Activated Fusible Link (CAFL).)

The advantages of the conventional fuse are the abundance of supply and the ease of use. A fuse, rated slightly above the maximum arcjet operating current, is connected in series with the thruster. In case the thruster failed and becomes a short path, the PCU will deliver a higher than normal current (say, twice the normal operating current) to blow open the fuse. The PCU should not have trouble delivering twice the maximum operating current to the short path, say 10-20 V, because the output power (V • I) is below normal despite the high current.

The drawback of the conventional fuse is its incapability of handling one scenario, when the thruster is partially conducting with a relatively high impedance. The leakage path will not allow the PCU to generate the high voltage pulse to start any thrusters, but at the same time, will impede high current to blow open the fuse in series with the malfunctioning thruster.

On the other hand, the EADD will have no trouble handling the above situation since its opening is independently controlled by an external triggering circuit rather than relying on the PCU's output current. It offers a true redundancy regardless of the thruster failure scenario. Unfortunately, there are very few sources of the EADD and they are very bulky.

We have identified only two manufacturers of EADDs. They are the G & W Electric Company and S & C Electric Company. Photographs of these products are shown in Figure 4 and 5 respectively. Both of them use explosives to open a conducting copper bar. These devices were originally designed for a high power A.C. transmission lines, and they were designed to work with a parallel small cross section current limiting fusible element. The fusible element is needed for interrupting high current with high voltage up to several thousand volts.

Because we want to be able to open the circuit even with no current flow (i.e. we can disconnect the thruster when the arcjet is off), we will use the disconnecting devices without the typical parallel fusible element. These devices can easily withstand several thousand volts after they are opened. Since the voltage of an arcjet system is in the order of several hundred volts, it is likely that these devices can interrupt high current without the fusible element. However, the manufacturers have no data to support this capability because the interrupting function of the standard product is usually served by the fusible elements. Fortunately, this capability is only desirable, but not a necessary requirement for this application.

For the G & W devices, the parallel fusible element is housed in a separate container. Therefore, the main disconnecting devices can be used without modification. For the S & C devices, the parallel element is housed in the same container as the main disconnecting device. A custom-made version, without the parallel element, is needed for our application.

These devices were designed for the utility power industry, therefore none of them were designed to meet military specifications. However, these devices are in hermetically sealed packages. Conversion to military parts should not be too difficult.

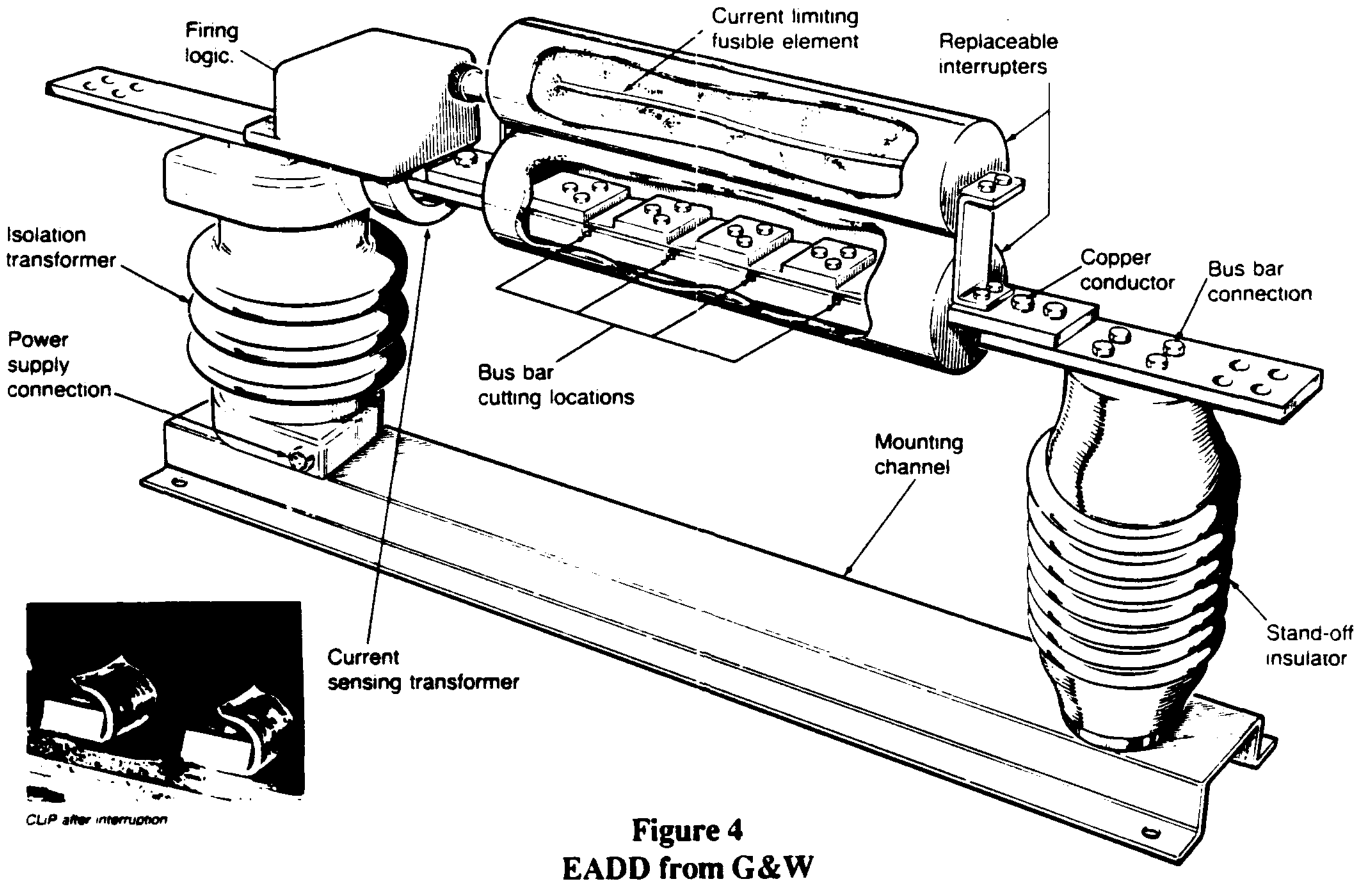


Figure 4
EADD from G&W

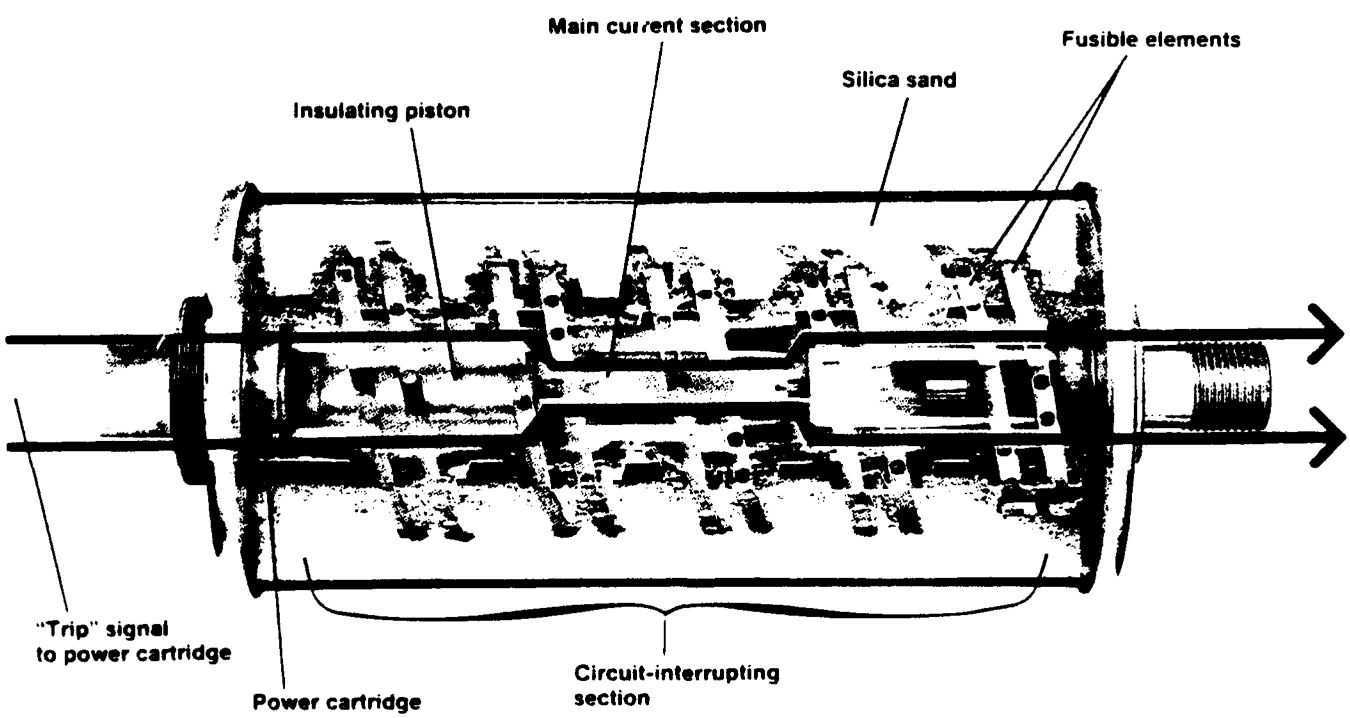


Figure 5
EADD from S&C

Start Pulse Suppressor

In the multiple thruster system, the high voltage start pulse, as well as the steady state voltage, are applied to all thrusters. If there is any breakdown, the breakdown will mostly occur at the high voltage pulses. As discussed in the section of "Unwanted gaseous breakdown in the idle thruster", the idle thrusters shall not respond to the high voltage pulses due to the absence of sufficient gas molecules. Therefore, we believe there should be no need for a start pulse suppressor. However, we want to be prepared if the high voltage pulse does have the potential to cause breakdown. In this section, we examine a technique for pulse suppression regardless of its necessity, which is addressed in other sections.

The whole idea of this program is to use one PCU with several thrusters without the use of high current, high voltage switches. Therefore, to simply use a conventional switch to block the high voltage is not an acceptable solution. In order to optimize the design, we must take advantage of the unique circumstance that the start pulse is a very narrow pulse (~500 nsec). Therefore, it is possible to put in a non-linear reactive component to reshape the narrow but high voltage pulse to a more benign form of energy. At the same time, the blocking characteristics of this component must be easily alterable so that it can pass the start pulse to the designated thruster.

Figure 6 shows the schematic of our proposed pulse suppressor circuit. A saturable inductor is designed to block to the start pulse. This inductor is somewhat different from a typical inductor in the sense that it has no air gap to store the magnetic energy (or distributed gap as in MPP cores). The reasons are:

1. We want the inductor to stay unsaturated only for a very short period of time (~500 nsec).
2. We want the high inductance to suppress the pulse. An air gap will significantly reduce the inductance.
3. We want the core to be easily saturable so that we can presaturate the core so that it does not behave like an inductor. This allows us to suppress the start pulses to selected thrusters only.

There are two possible ways to switch off the pulse suppressor (change its reactance), both of them using an additional winding. We can pass a D.C. current through the additional winding to presaturate the core or connect the additional winding to a low impedance load to reflect a low insertion impedance. Both of these will significantly lower the reactance of the inductor and therefore the high voltage pulse can pass through the inductor to the thruster with minimum distortion.

Since these methods utilize the non-linear effect, or the saturation, of the core as the switching mechanism, the gain (the impedance difference between on state and off state) of the switching is not as good as a typical semiconductor switch. We cannot expect to see the start pulse completely disappearing from the idle thrusters. Fortunately, we do not need to completely eliminate the start pulse to prevent breakdown. The start pulse is about 2000 V. It may have a potential to breakdown

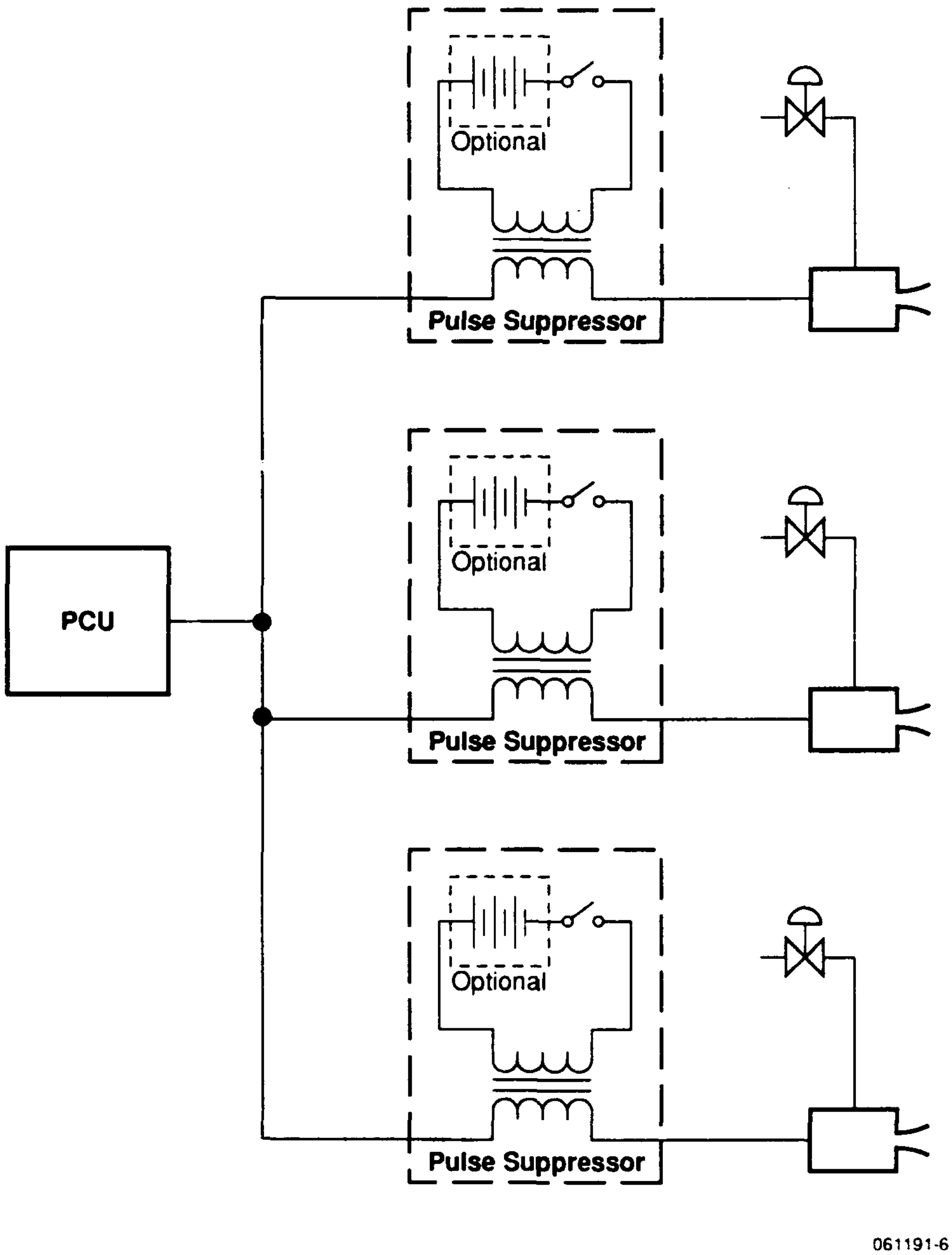
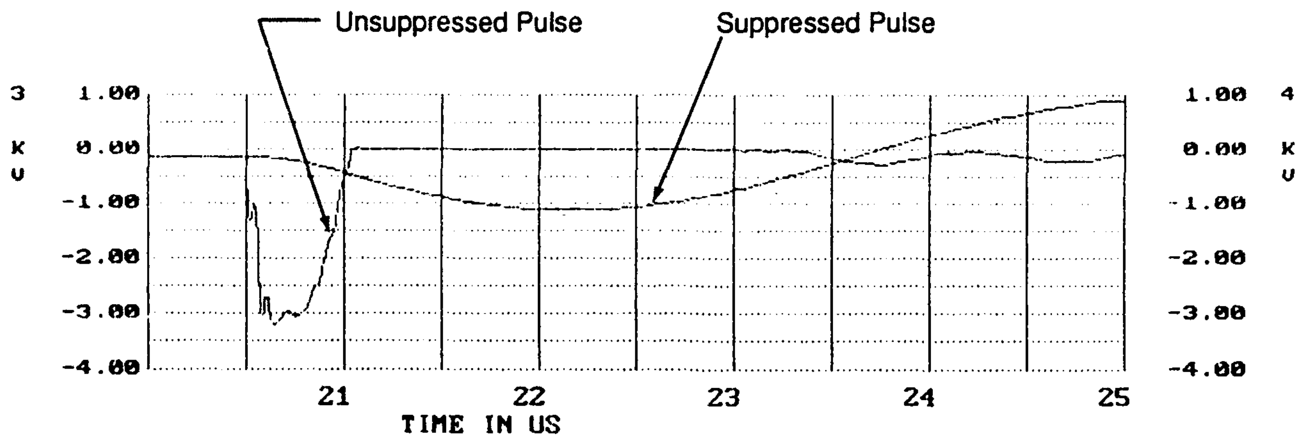


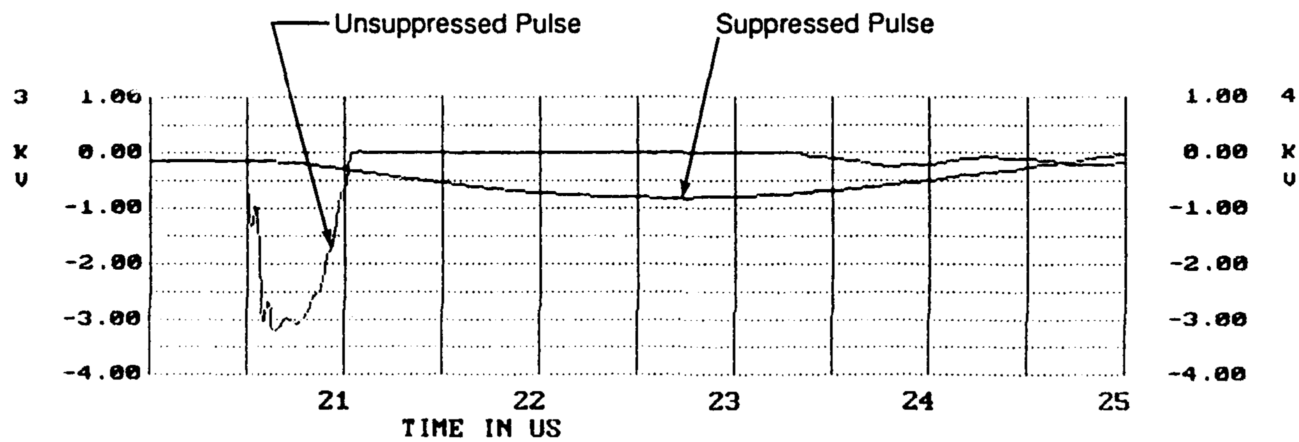
Figure 6
Multiple Thruster System with Pulse Suppressor

the idle thrusters. If a saturable inductor can reduce its voltage from 2000 V to, say 600 V, the chance of breaking down is removed. This type of amplitude reduction is what we believe achievable by the saturable inductor technique.

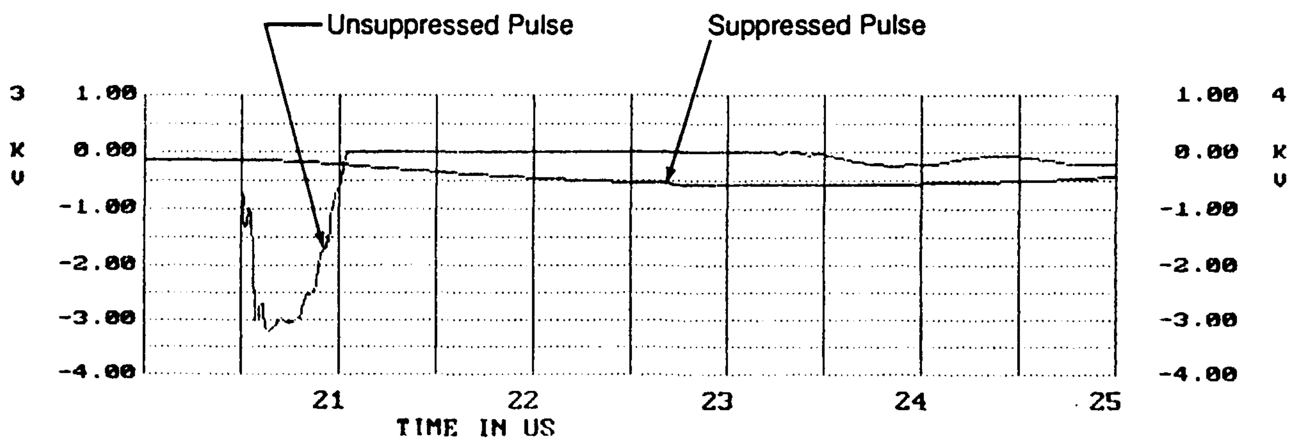
We have performed some circuit simulation to evaluate the effectiveness of the suppressor inductor. Figure 7a, b, and c show the results of the suppression with 1, 2 and 4 mH suppressor inductors respectively. Based on the above result, we feel that a suppressor inductor of about 2 mH is a reasonable choice because it keeps the pulse voltage at about 800 V.



a. 1 mH Suppressor Inductor



b. 2 mH Suppressor Inductor



c. 4 mH Suppressor Inductor

Figure 7
Pulse Suppressor with Different Inductance

The degree of the suppression is proportional to the weight and size of the inductor. Therefore, if the start pulse suppression is necessary, we should optimize the weight and size of the inductor by determining the maximum voltage pulse an idle thruster can tolerate without risk of breaking down.

Controller For Multiple Thruster Arcjet System

Whether using a conventional fuse or an EADD, a controller is needed to coordinate the operation of the thruster, the timing of the propellant flow and the opening of the fuse or other disconnecting device. The following is a summary of the functions that a multiple thruster controller has to perform.

1. To determine whether a thruster is functioning properly.

2. To detect a short or leakage path in a thruster.

3. To blow open a fuse or to trigger the disintegration of an EADD.

4. To determine the status of the thrusters.

5. To switch on the propellant to the appropriate thruster.

We have designed a controller for multiple thruster arcjet systems. A simplified schematic is shown in Figures 8, 9, 10 and 11. The flow chart of the controller is shown in Figure 12. This controller is designed for a system using an EADD. However, it can easily be converted to a conventional fuse system. For systems using an EADD, a signal is sent to activate the explosive of the EADD when an unrecoverable short is detected. For systems using conventional fuses, this disconnecting signal should be sent to the arcjet PCU so that it will increase its current to blow open the fuse. Furthermore, there is no need to turn off the arcjet thruster before attempting to disconnect it because the disconnection is achieved by the increase of output current. It should be noted here that there is an additional benefit of using the conventional fuse. When we increase the output current to blow the fuse, the shorted path may be burned open before the fuse. In this case, the arcjet system can actually be recovered without switching to another thruster.

The following is the simplified theory of operation of the controller. A flow-chart is shown in Figure 12.

Startup. As soon as the controller receives the arcjet operation request, the controller will turn on the propellant to the appropriate thruster and then generate a high voltage start pulse after a short delay (see Figure 9). At this time, the appropriate thruster has already been selected by the Thruster Register. This selection is based on previous operation and the information is stored in the Thruster Register.

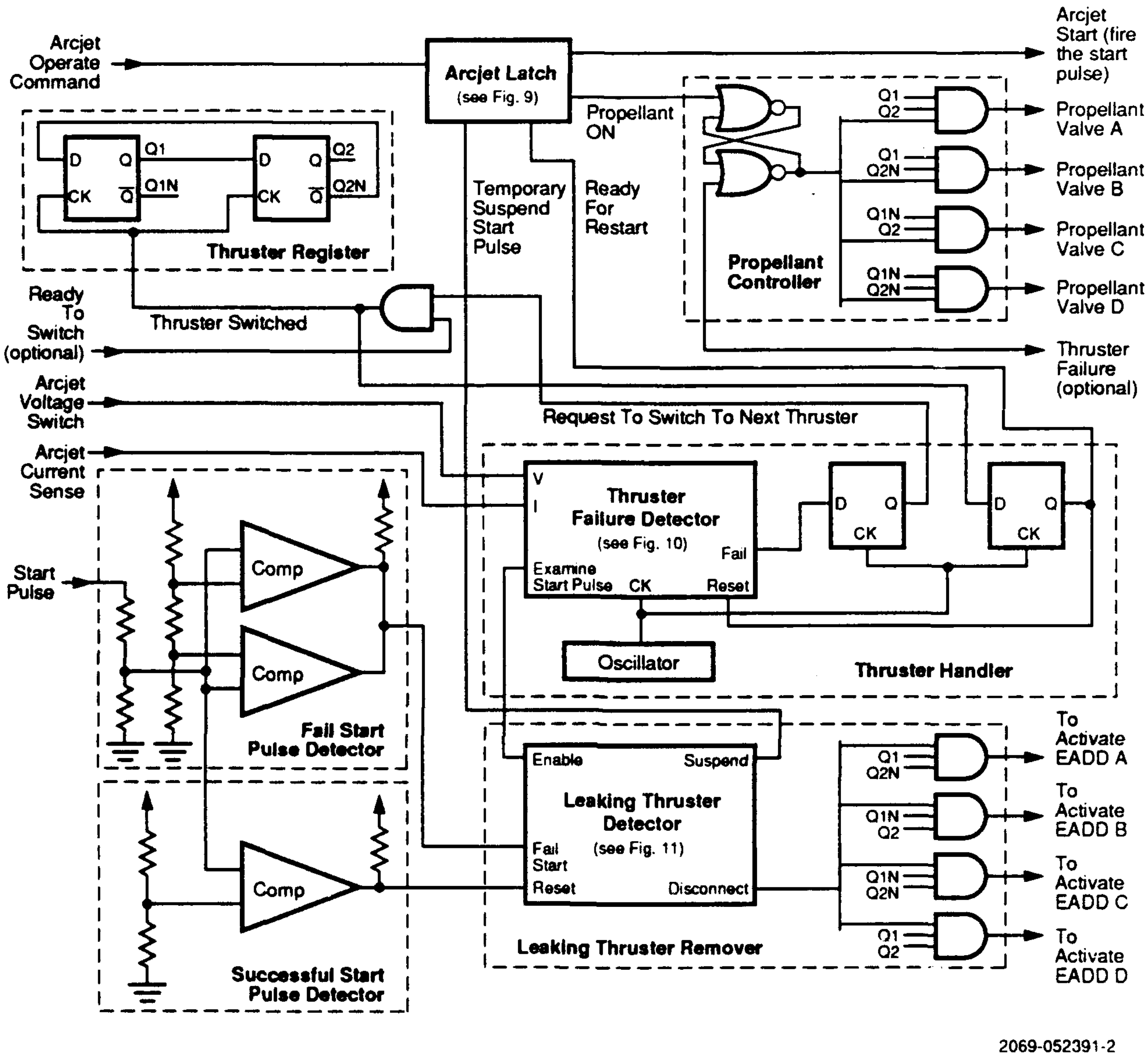


Figure 8
Multiple Thruster Controller Simplified Schematic

If the start attempt is successful, the arcjet will transition to steady state operation. If the arcjet failed to start, the controller will automatically attempt to restart the arcjet. In order to determine whether a leakage path was created by the previously failed thruster, a watch-dog circuit is used to monitor the high voltage start pulses. Start pulses that are below a threshold value will be logged. If eight of the low voltage pulses occur in a row, the controller will assume that a leakage path exists and will transmit a signal to activate the EADD to disconnect the last failed thruster. After the disintegration of the EADD, the controller will resume its start attempts.

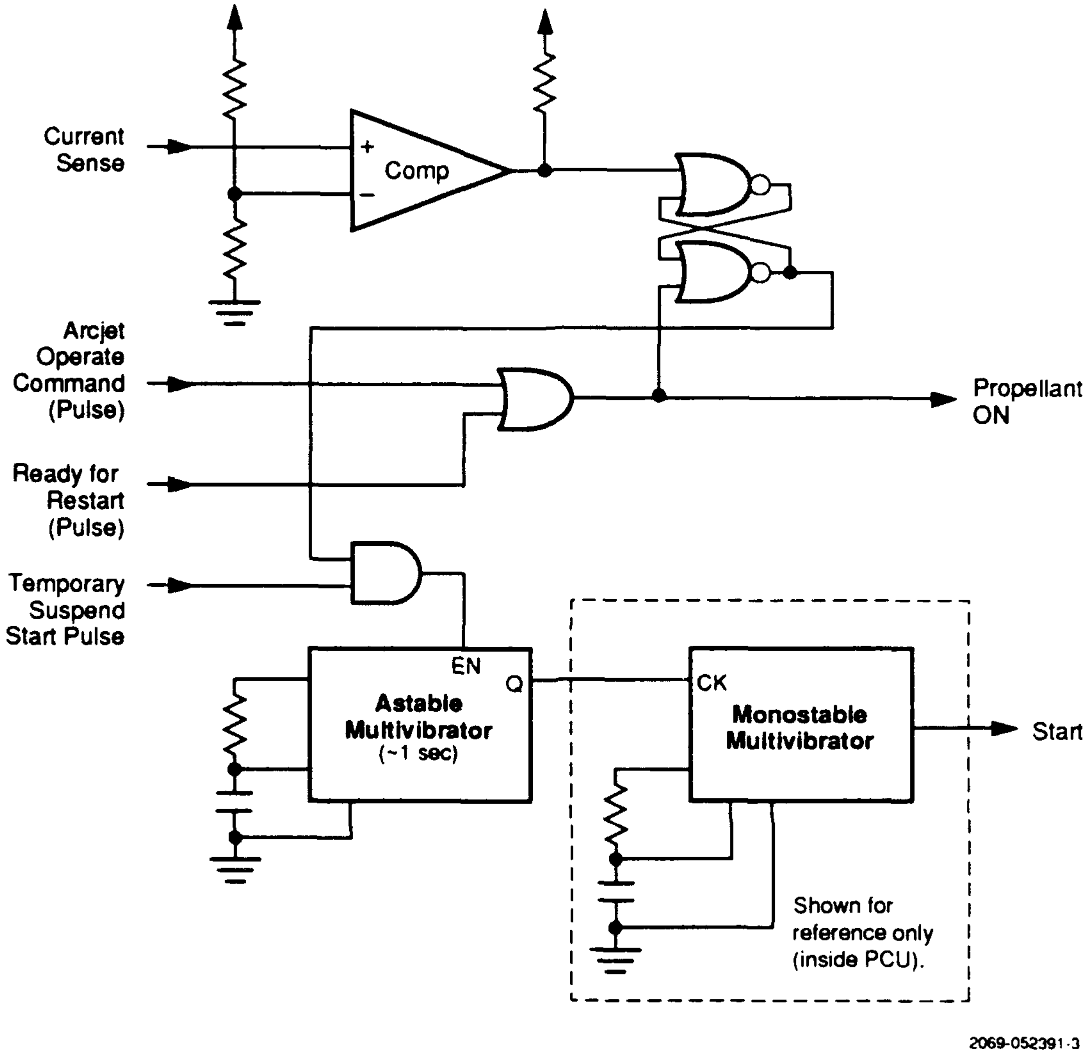


Figure 9
Arcjet Latch

Steady State Operation The steady state operation will continue until one of the following two conditions happen:

1. Successfully completes the assigned task and the operation is terminated by spacecraft computer or ground control.
2. A fault occurs. (Either the controller terminates the arcjet operation as a fault is detected or the fault causes the thruster to cease operation.)

The controller continuously monitors the voltage and current of the arcjet and uses the measurements to determine whether steady state operation is normal. A very complicated and

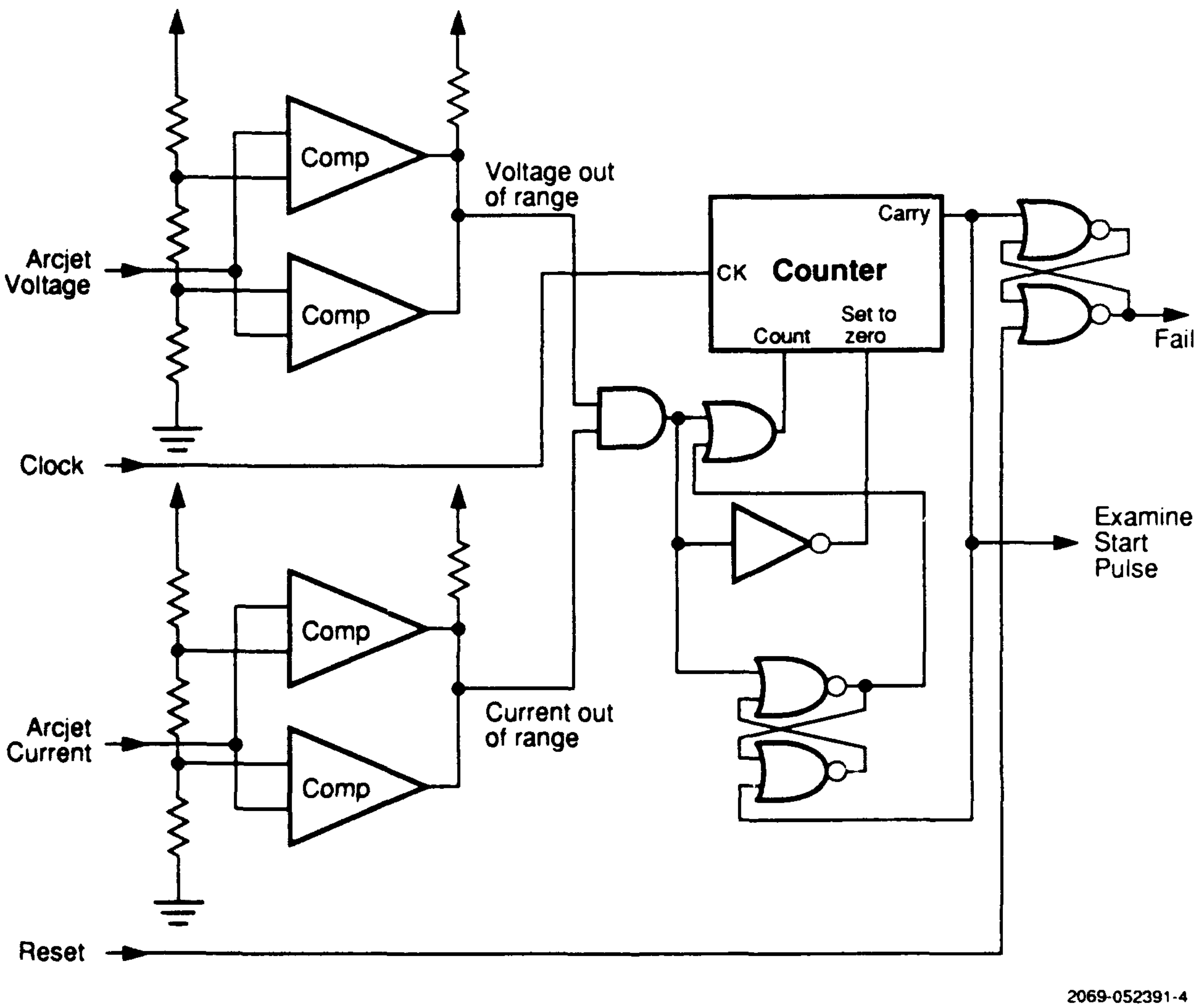


Figure 10
Thruster Failure Detector

intelligent circuit which takes into account many parameters could be used to determine the normality of the operation. In our design, only a simple comparing circuit is used to determine the abnormal operation. If any out-of-range condition is detected, the controller will turn off the arcjet after a short delay. This delay, in addition to avoiding shut down caused by temporary fluctuation or measurement noises, provides the capability of automatic recovery.

The arcjet system will attempt to recover from the faulty condition before it switches to another thruster. In realty, this function is just an intrinsic characteristic of the arcjet PCU. The arcjet PCU will try to maintain a constant current regardless the impedance of the arc. (Note: An arcjet PCU usually operates in constant current mode or constant power mode. For constant power

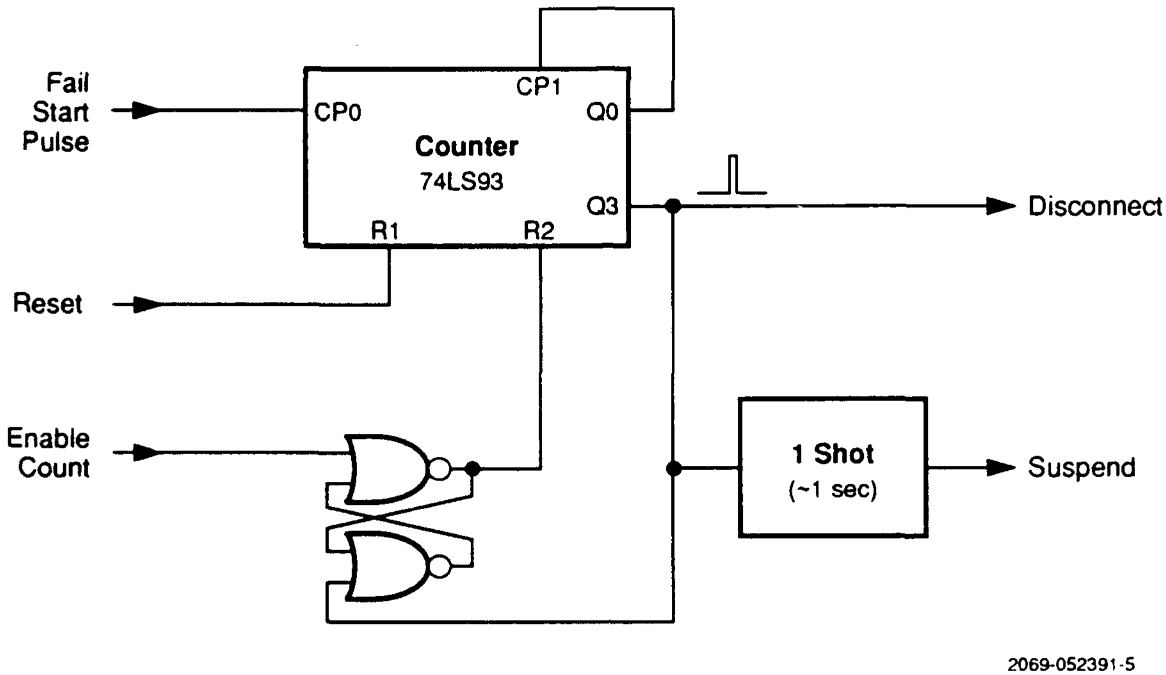


Figure 11
Leaking Thruster Detector

mode, the PCU continuously adjusts the arcjet current to maintain a constant power. However, the range of adjustment of the arcjet current is rather limited. It should not be difficult to pose a limit on the range of the arcjet current even in a constant power mode. With this limitation, the above statement is valid, for practical purposes, even in a constant power operation.) Therefore, if there is a short path created by a whisker, the PCU will continue operation and supply the same amount of current to thruster and, hopefully, burn open the short path. The part of the controller that performs this function is a simple delay circuit that makes the system able to tolerate an abnormal operation for about a second, or whatever length is adequate, before shut down. If the abnormal condition persists, of course, the controller will turn off the propellant and the thruster, then switch to another thruster.

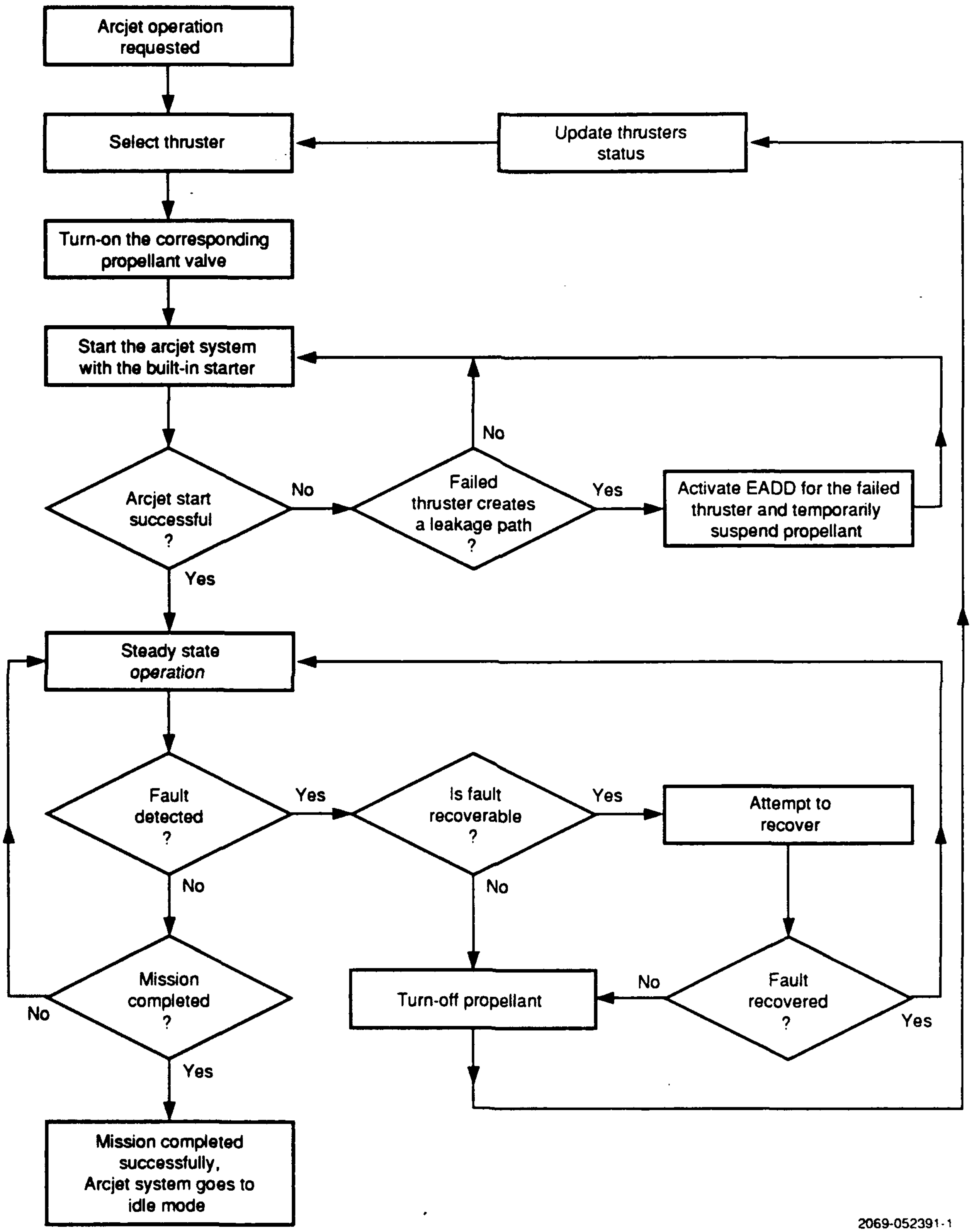


Figure 12
Multi-thruster Controller Function Flow Chart

SUMMARY OF THE RESULTS

Survey

We identified two major issues from this task, namely the unwanted breakdown in the idle thrusters and the short-circuit failure. The first one is discussed in the next section and the second one is discussed in the following section.

Breakdown

We share the concern of the unwanted breakdown with our survey respondents. The likelihood of breakdown is related to the gas pressure around the idle thrusters. The gas pressure caused by the propellant was analyzed with an equation for a simple point source model. The result was encouraging because the estimated pressure is an order of magnitude below the threshold level that can cause breakdown. The propellant switching technique may work with no modifications.

If the unwanted breakdown is still a concern, a plume shield technique was also suggested to reduce the pressure around the idle thrusters, and a pulse suppressor technique was suggested to reduce the voltage pulse to the idle thrusters. These two techniques, when used, will further reduce the chance of the unwanted breakdown.

Even though we are encouraged by the result of the analysis and believe that the unwanted breakdown is not a serious problem, it is difficult to completely eliminate the possibility of the breakdown. Tests should be performed in Phase II to demonstrate a reliable operation.

EADD

Fuses or EADDs (Externally Activated Disconnecting Device) are proposed to be put in series with all thrusters so that they could be used to disconnect a failed thruster when it becomes a short-circuit. Fuses are easier to use and have more selections but fail to work if a damaged thruster becomes a high impedance short-circuit. EADDs are available and they seem to satisfy our requirements. However, they are designed for the utility industry and need modification before they can be used in this capability.

We feel, at this time, the important question to answer is whether a thruster is likely to fail as a short-circuit. Many of the people working with arcjet systems believe the chance of this type of failure is very remote. Some argued that this scenario cannot be ignored.[3] We do not have enough data to make the judgement. However, we do feel that this issue should be the resolved in Phase II as soon as possible before more effort is spent in the area of fuses and EADDs, which may become unnecessary and irrelevant.

If disconnecting devices are necessary, we need to decide between the conventional fuse and the EADD. Pros and cons were also discussed in this section.

Suppressor

If there is a reasonable chance for an unwanted breakdown at the start pulse, a switchable pulse suppressor inductor could be used to reduce the peak voltage of the start pulse to the idle thrusters to minimize the chance of unwanted breakdown. A computer simulation showed that a 2 mH inductor could reduce a 3000 V pulse to about 800 V. This voltage reduction greatly reduces the chance of breakdown.

Application of this circuit will add complication and cost to the arcjet system, therefore we recommend to use this technique only when it is proven necessary. When it is used, a minimum suppression should be used to minimize the weight and size of the suppressor inductor.

Controller

We finished the preliminary design of a controller for multiple thruster arcjet system. A set of simplified schematics and a flow-chart are presented in this final report. The controller is designed for an EADD system but could be modified for conventional fuse with minimum effort. This preliminary design helps define the interface between different subsystems.

RECOMMENDATIONS

The approach of using propellant to select thruster is not only innovative, but also has good financial payoff. Even with the concern of unwanted breakdown and short-circuit failure, there is no evidence that the multiple thruster system will not work as we proposed originally. Based on the analysis performed in Phase I, the unwanted breakdown should not happen. Neither is there any evidence that a thruster is likely to fail in a short-circuit condition. This would be a very improbable event because small short circuits can be burned open again.

Propellant switching is an attractive alternative compared to mechanical / solid state switches to transfer power between arcjets, which are a significant operational risk in themselves. The small chance that shorted thrusters or unwanted breakdown may interfere with propellant switching could have a lower risk than the reliability of other switching. Furthermore, these potential problems could be accommodated as we have, in the Phase I program, prepared several alternatives to handle the above mentioned scenarios should they occur.

The important tasks in Phase II should include:

1. Experimentally determine the risk of unwanted breakdown in the idle thrusters.
2. If the risk of unwanted breakdown is real, determine the effectiveness of the plume shield, pulse suppressor, and possibly other techniques in reducing the risk of unwanted breakdown.
3. Survey existing data, interview experts, and analyze the probability of a thruster becoming a short-circuit.
4. Perform a trade study comparing the conventional fuse and the EADD, if they are necessary as determined in Task 3.

A road map of these tasks is shown in Figure 13.

REFERENCES

1. Private conversation with F. Curran and J. Hamley in NASA LeRC.
2. Internal Report for "The Effects Of Effluent Clouds Upon Orbiting Spacecraft and Systems" K. Koester, 2/26/1987

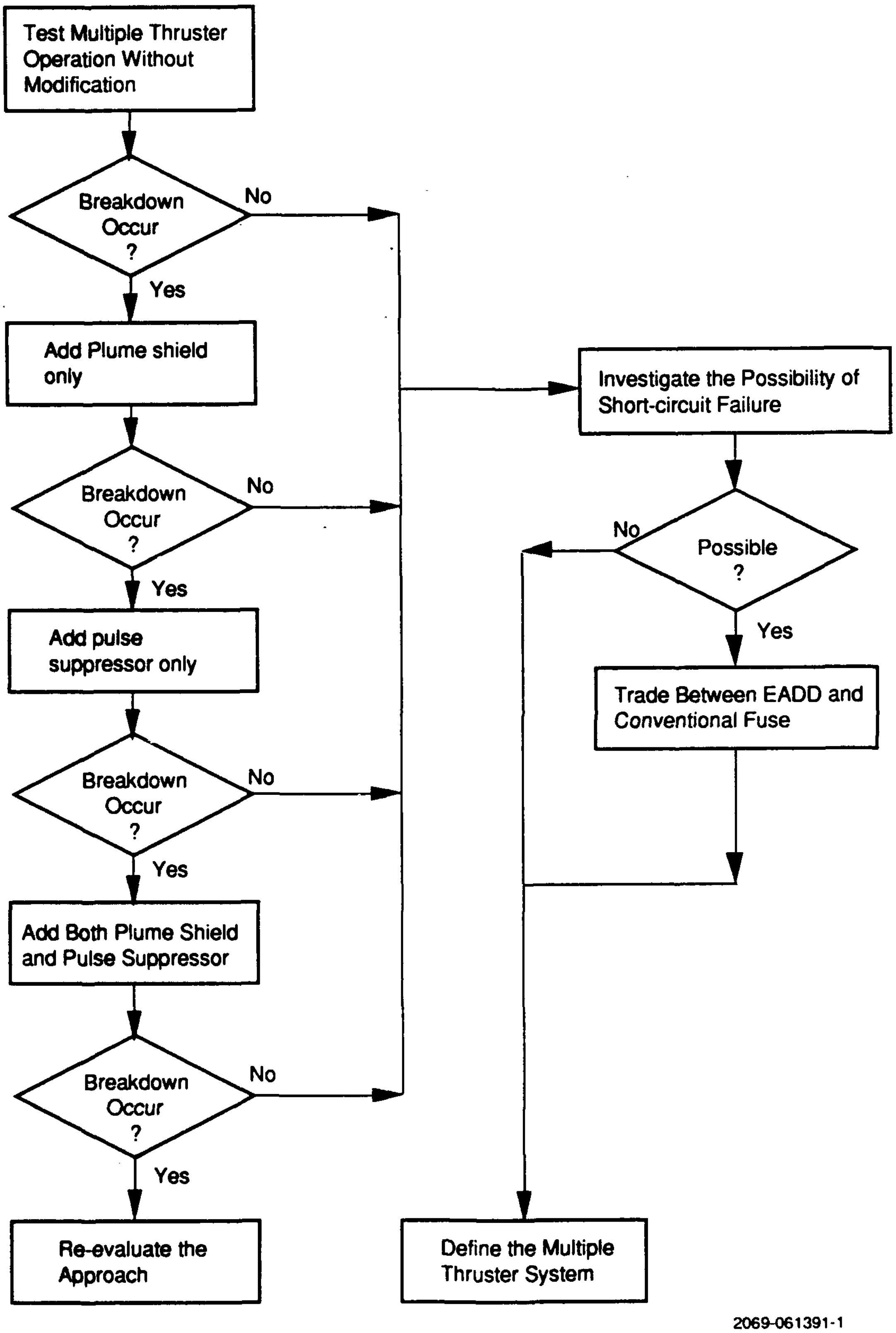


Figure 13
Road Map for Phase II Task